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OPTICAL PULSATIONS IN HZ HERCULIS. V.
PULSE-RESOLVED SPECTROPHOTOMETRY

Bruce Margon
Space Sciences Laboratory, University of California, Berkeley

Arthur Davidsen
Department of Physics, The Johns Hopkins University

and

Stuart Bowyer
Department of Astronomy and Space Sciences Laboratory
University of California, Berkeley

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ABSTRACT

We have obtained digital spectra of HZ Herculis with 10 Å resolution in the λλ3600 – 6000 Å region, synchronously dividing the 1.24-s optical pulsation period into eight 155-ms phase bins. The optical pulses are detected in the data, but their fractional amplitude is only 0.08 percent, a factor of 4 less than typically observed. The separate spectra of each one-eighth of the pulse are identical to within the statistics of the observation. If the X-ray to optical pulse reprocessing mechanism concentrates the optical pulsations into discrete spectral line features, our data require the pulses to be distributed among more than four such lines.

Subject headings: pulsation – stars: individual – X-rays: sources

I. INTRODUCTION

HZ Herculis, the binary companion of the X-ray pulsar Hercules X-1, is now well known to exhibit optical pulsations with a period similar to that of the X-ray source. These pulsations, which do not exceed 0.003 mag in amplitude, were discovered by Davidsen *et al.* (1972, hereafter Paper I), and the complex behavior of their frequency and amplitude with time has been discussed in some detail by Middleditch and Nelson (1973, 1976: hereafter Papers II, IV). On most nights the frequency of the observed pulses differs slightly (by about 150 km s^{-1}) from that of the X-ray pulsar, which when combined with the known geometry of the system indicates that this light originates from the limb of HZ Her, presumably as a result of reprocessing of the 1.24 sec X-ray pulses incident from Her X-1. Thus the frequency of the pulses can be used to derive the velocity curve of HZ Her, and the resulting inferences are discussed in Paper IV. However, aside from their use as a velocity-tracer in the system, the pulses contain information on a separate but equally interesting problem: the physics of the X-ray-to-optical pulse reprocessing mechanism. Basko and Sunyaev (1973), and Basko, Sunyaev, and Titarchuk (1974) have pointed out that certain such mechanisms may preferentially enhance the amplitude of the optical pulsations in the stellar emission lines. In Paper III (Davidsen, Margon, and Middleditch 1975), we presented the first experimental data relevant to this issue, in the form of a crude attempt to determine the energy distribution of the optical pulsations, using a narrowband

interference filter. The results indicated a substantial enhancement of the amplitude of the pulsations in a 100 Å wavelength band centered at λ4666, when compared to unfiltered observations. This was interpreted as evidence for preferential reprocessing of the X-ray pulses in one or more of the prominent emission lines in this region, He II λ4686 and N III λ4634 - 4641.

The observational technique employed in Paper III had several undesirable limitations. Only a small section of the spectrum could be observed in one night, and then only with very poor wavelength resolution (100 Å). In addition, no information could be obtained on the existence and strength of the emission features of interest simultaneous with the collection of the pulsation data. This is a special difficulty because the emission line strengths in HZ Her are known to be very highly variable (e.g. Crampton and Hutchings 1974). In this Letter we describe a new and unique observational technique which we have developed to overcome these difficulties, and report our first observational results.

II. PULSE-RESOLVED SPECTROPHOTOMETRY

The ideal technique to study this problem would simultaneously employ high wavelength and time resolution throughout the visible spectrum. To achieve as much of this goal as practical, we have developed a set of hardware and software additions to the Robinson-Wampler Image Tube Scanner (ITS), employed with the Cassegrain spectrograph of the Lick

Observatory 3-m telescope (Robinson and Wampler 1972). The grating used yields approximately 10 Å resolution throughout the 3600 - 6000 Å band. In ordinary operation, the ITS reads out one scan of the entire spectrum each 4 ms from separate star and sky slits and cumulatively stores this information in 4096 channels of a rotating digital memory for the length of the desired observing run. At the termination of the observations, the data are read into the core memory of a minicomputer, where they can then be sky-subtracted, normalized, displayed, and stored in a variety of different modes. For our observations a quartz-crystal clock is used to divide the 1.24-sec pulse period of HZ Her/Her X-1 into eight equal phase bins of approximately 155 ms each. After each 155 ms, the clock supplies the computer with an interrupt, and the rotating memory is read into one of eight sections of the minicomputer core storage; the observations then resume. In this manner the entire spectrum of each one-eighth of the pulsar period is accumulated coherently and independently for any desired length of time. At the termination of a run, all eight stellar spectra plus the sky spectrum (accumulated continuously throughout the run) are read onto magnetic tape for subsequent analysis. However, the clock remains running between data accumulations to provide a coherent time base all night, and the computer requires each new run to begin at the same pulsar phase bin. Thus all separate runs are coherent and can later be added together to improve the statistical significance of the data, as long as the selected clock frequency corresponds closely to the actual mean pulsation frequency for the night.

The design of the system provides several useful checks for systematic problems in the accumulation procedure. The photometric standard stars ordinarily observed with the ITS for purpose of absolute flux calibration are also observed with our apparatus; the eight resulting spectra have the same shape and intensity to within the statistical accuracy of the total counts collected. This proves the clocking procedure itself is not introducing a 1.24-sec modulation into the spectral shape or total intensity of the data. A second check is provided by the existence of eight completely independent spectra simultaneously accumulated over the same time interval; this enables the reality of weak spectral features to be easily verified and makes the noise level of the data readily apparent. Finally, the individual photopulses are also read off the phototube prior to entering the rotating memory and the ITS software. This purely photometric (no wavelength resolution) data is then recorded on magnetic tape using electronics independent of the apparatus described above. The resulting tape is Fourier analyzed with the same computer code described in Papers I - IV, to provide independent information on the amplitude and exact frequency of the optical pulsations.

III. OBSERVATIONS

The data described here were obtained on 1975 June 15 from 0515 through 1053 UT, during which time HZ Her was observed continuously, with the exception of occasional one minute gaps necessary to write data to magnetic tape. These 5.5 hr of data yielded approximately 4×10^8 detected counts. Therefore the time-averaged total spectrum is of extraordinary accuracy and detail, and the features of this spectrum will be discussed elsewhere. Here we are concerned only with possible variation of the spectrum with the 1.24-sec pulsar phase.

The time period of the observations spanned phases 0.72 - 0.86 in the 1.7 day binary period. In the 35-day X-ray periodicity of the system, this time is approximately 5 days prior to X-ray turnon (cycle 4 in the notation of Paper IV), as calculated from the ephemeris of Davison and Fabian (1974), and the actual observations of the X-ray turnon of the previous two cycles from OAO-C and Ariel 5, kindly communicated by Dr. P. Davison. The extensive Lick observations (Papers I - IV) show that optical pulsations are reliably observable at this combination of 1.7 and 35-day phases. In particular, we stress again that optical pulsations are consistently detectable during the X-ray off phases of the 35-day period, which is not in good agreement with theories which attribute the cessation of X-ray flux at Earth to a modulation of the accretion rate (e.g. Lamb et al. 1975).

The Fourier transform of the photometric data from this run indicates that pulses were in fact detected as expected. The apparent frequency of the detected pulsations, $\nu = 0.8078061 \pm 0.0000062$ Hz, corresponds to a HZ Her/Her X-1 barycentric velocity of -20.2 ± 2.3 km sec^{-1}, in agreement with the frequency expected for this binary phase ("Feature II" in the nomenclature of Paper IV) Our preset signal averaging period and the actual pulsar period differed by $\Delta P/P = (1.2 \pm 0.8) \times 10^{-5}$, permitting analysis of $\sim$1-hr segments of data without a phase shift larger than one of our 155-ms phase bins. Longer stretches of summed data could have somewhat reduced pulse amplitude.

As usual there is no evidence in the Fourier transform for the presence of higher harmonics. The excess power in the detected feature decreased through the course of the night, again as expected for this phase as Her X-1

approaches its eclipse some 8-hr later. The amplitude of pulsation in the first 4.5-hr of data is 57 counts s^{-1}, which corresponds to a mean pulsed fraction of $(7.5 \pm 1.5) \times 10^{-4}$. The detected feature appears at 15.5 exponential levels above the mean local power level and has an associated accidental occurence probability of 2×10^{-7}; there is therefore no doubt that the data discussed here do contain the usual pulsations, although their strength is about a factor of 4 below those discussed in Paper III. We stress this point because on a randomly selected night the pulsations are not generally observable at Earth, and so no inferences may be made on the short timescale behavior of the emission lines unless the pulsations are proven to be present. For example, in the entire 1975 observing season, there were less than 6 nights during the dark-of-the-moon that had the proper 1.7 and 35-d phases for strong pulsations.

As the night progresses and the X-ray source approaches eclipse, our spectra clearly show a decrease in effective temperature and excitation of the portion of HZ Her visible at Earth: the emission lines become weaker and the Balmer absorption lines deeper progressively through the data. However, the HeII λ4686 line and CIII - NIII λλ4640-4650 blends, noted by many observers, are present in all the spectra. A surprising result is that our spectra show a very large number of other previously unreported emission lines which are equally prominent. For example, NV λ4619, possibly also containing a component due to NII λ4621, is present at a strength exceeding the previously noted NV λ4603 (Crampton and Hutchings 1974). These lines have an excitation potential of 60 eV, and thus have interesting consequences for soft X-ray emission from Her X-1 which will be discussed elsewhere.

Due to the changing line strengths and the possibility of accumulated phase errors, we have analyzed the data in 30-min segments to search for pulsations. As a first step, the total number of counts in each of the eight spectra is calculated. This signal-averaged photometric data may then be examined for the presence of the pulse. In all cases, even when the emission line strengths are weaker than their peak strengths, these eight sums indicate the existence of a sinusoidal pulse of amplitude in agreement with (although much less well-determined than) the Fourier transform. Thus we are assured that all of our spectra do indeed contain pulsations. As pointed out in Paper III, because the number of nights on which emission is visible exceeds the number of nights on which pulsations are detectable, a simple relationship between line strength and pulsation amplitude is precluded.

In Figure 1 we present a sample of the pulse-resolved spectrophotometric data. These data were acquired from 0515 through 0610 UT, centered at binary phase 0.73. The upper panel of the figure is the time-averaged mean spectrum of all eight bins during this interval; it has been converted to an absolute flux scale through the observation on this night of three standard stars from Oke (1974). Numerous emission features are visible in addition to the prominent Balmer absorption spectrum. A convenient mode of analysis is to subtract this mean spectrum on a channel-for-channel basis from each of the eight original spectra. These eight residual spectra then provide a convenient definition of the noise level in the data, and also allow a simple visual search for phase-dependent variations. The result of this procedure appears in the lower panel of the figure, where the eight curves are the difference of each spectrum from the mean, plotted as a ratio of this difference to the mean itself. It is obvious that there are no phase-

dependent features which substantially exceed the general noise level. Similar diagrams have been generated for each subsection of the data and the entire night of data as a whole; in no case is there positive evidence for any wavelength-dependence of the pulse amplitude.

IV. DISCUSSION

For both theoretical purposes and for comparison with Paper III, the only other observational data on this subject, it is desirable to quantify the limits on any wavelength dependence of the pulsed light. The statistics of a signal-averaged observation such as this are complex, among other reasons because the grating efficiency makes the total number of collected counts quite wavelength-dependent over our $\lambda\lambda$3600-6000 Å band, and in photon-counting image tube systems many single-photon events are multiply counted. We feel the most conservative error estimator is defined by the scatter in the data itself. Therefore we have calculated limits on wavelength-dependent phenomena as follows . Over any desired wavelength interval, the total number of counts in that interval for each of the eight phase spectra defines a crude, eight-point light curve for which a characteristic amplitude may be calculated. This calculation may be repeated for many adjacent wavelength intervals, and if the total number of intervals analyzed is restricted to the same $\sim$ 600 Å of spectrum, there are approximately the same number of detected events per bin. The resulting list of fractional modulations then defines a mean and sample variance without further assumption. We then adopt 3 standard deviations above the sample mean as a crude but quantitative estimator of the upper limit on any wavelength-dependent pulsation enhancement.

Because there are many possible variables involved, for example, length of data run utilized or emission line strengths during the run, we cite two contrasting cases to illustrate the sensitivity of the observations. From 0515-0610 UT (the data of Figure 1), the star is hot, has intense emission lines, and is pulsing with the highest amplitude of any time during the night (which is still, however, relatively low in comparison with data in Papers I - IV). Our upper limits on pulsed fractional half-amplitude of spectral features during this period are 0.016 on any 100 Å of spectrum from 3900-6000 Å, and 0.04 on any 10 Å feature from 4200-6000 Å. From 0613-0804 UT the star is fainter, has somewhat weaker emission lines, and has an even lower overall pulsed amplitude. The limits during this interval are 0.011 for any 100 Å in the 3900-6000 Å range, and 0.03 for any 10 Å from 4200-6000 Å. In both cases the limits are weaker ($\sim$0.10) for narrow features at $\lambda <$ 4200 due to low count rates.

In Paper III we reported observations on two nights of enhanced modulation in the 100 Å band centered at 4666 Å. We found that the pulsed fraction in this band was $\sim$2.5%, or a factor of 8 greater than the 0.3% pulsed fraction of the broadband data on those nights. Our current limit of less than a factor of 21 enhancement (=0.016/0.00075) in any 100 Å band is therefore consistent with the earlier results. If the broadband pulsed fraction in the present data had been as high as that observed in Paper III (at different phases in the 1.7- and 35-d periods), the predicted enhancement would have been easily detected. Our reduced sensitivity in the present data results from the very small total modulation which occured during these

observations. The use of the 3-m telescope in place of the 0.6-m telescope (Paper III) does not compensate for this reduced modulation, because the lower throughput of the spectrograph-scanner system compared with a photomultiplier tube and the added random noise resulting from multiply counted events combine to offset partially the advantage of the larger collecting area.

The technique employed here does have an important advantage over that of Paper III, in that the resolution is vastly improved and the entire visible spectrum is studied simultaneously. The observations reported in Paper III lead us to conclude that approximately one-third of the total optical pulsations should be attributed to He II λ4686 and/or N III λ4640 emission lines. Because at that time there were only a small number of reported emission lines in the HZ Her spectrum, we further speculated that all of the optical pulsations might be associated with a few such lines.

The current data allow us to further comment on this hypothesis. If the observed 0.0008 mag pulsations were concentrated in one 10 Å interval rather than a truly broadband distribution over $\sim$2000 Å, the resulting factor of 200 enhancement would cause an easily detectable 15% modulation in this narrow band. Our derived upper limit of 4% modulation for any 10 Å interval in the spectrum therefore requires that more than four spectral lines must contribute if the pulses are in fact associated with lines, i.e., no single line is responsible for more than one-fourth of the total observed pulses. This is consistent with, and an extension upon, the results of Paper III, where a maximum single-line contribution of $\sim$0.30 (+0.10,−0.20) was suggested for λ4686 or λ4640.

If the broadband pulsed fraction in the present data were as high as that in Paper III, we would have a much stronger limit on the number of contributing lines, or if only a few lines are responsible for the pulsations, these would have been detected. However, the spectra presented in Figure 1 reveal the presence of a large number of previously unsuspected emission lines, and it is possible that many of these contribute to the observed optical pulsations. If this is indeed the case, it will be difficult to establish which lines are contributing and to what degree. It has taken over 500-hr of broadband photometry (cf. Paper IV) to elucidate the nature of the time dependence of the frequency of the optical pulsations; it is perhaps, therefore, not unexpected that the energy distribution of the pulsations may be equally complex.

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Stuart Bowyer and Bruce Margon: Space Sciences Laboratory, University of California, Berkeley, California 94720

Arthur Davidsen: Department of Physics, The Johns Hopkins University, Baltimore, Maryland 21218

FIGURE CAPTION

Figure 1. Pulse-resolved spectrophotometry of HZ Herculis, obtained from 0515-0610 UT on 1975 June 15 with the Lick Observatory 3-m reflector. Upper panel: the time-averaged spectrum during this interval, with the flux f_ν in units ergs cm^{-2} s^{-1} Hz^{-1}. The observations yield B = 13.3, B-V = -0.1. Lower panel: The difference of the spectrum of each eighth of the pulsar period from the time-averaged spectrum, expressed as a ratio of this difference to the mean spectrum. Maximum light (peak of the pulse) occurs near phase bin 6. The noise level increases for $\lambda < 4000$ Å due to the decreasing instrumental count rate. The vertical bar in the upper right indicates the scale of a 5% fluctuation.

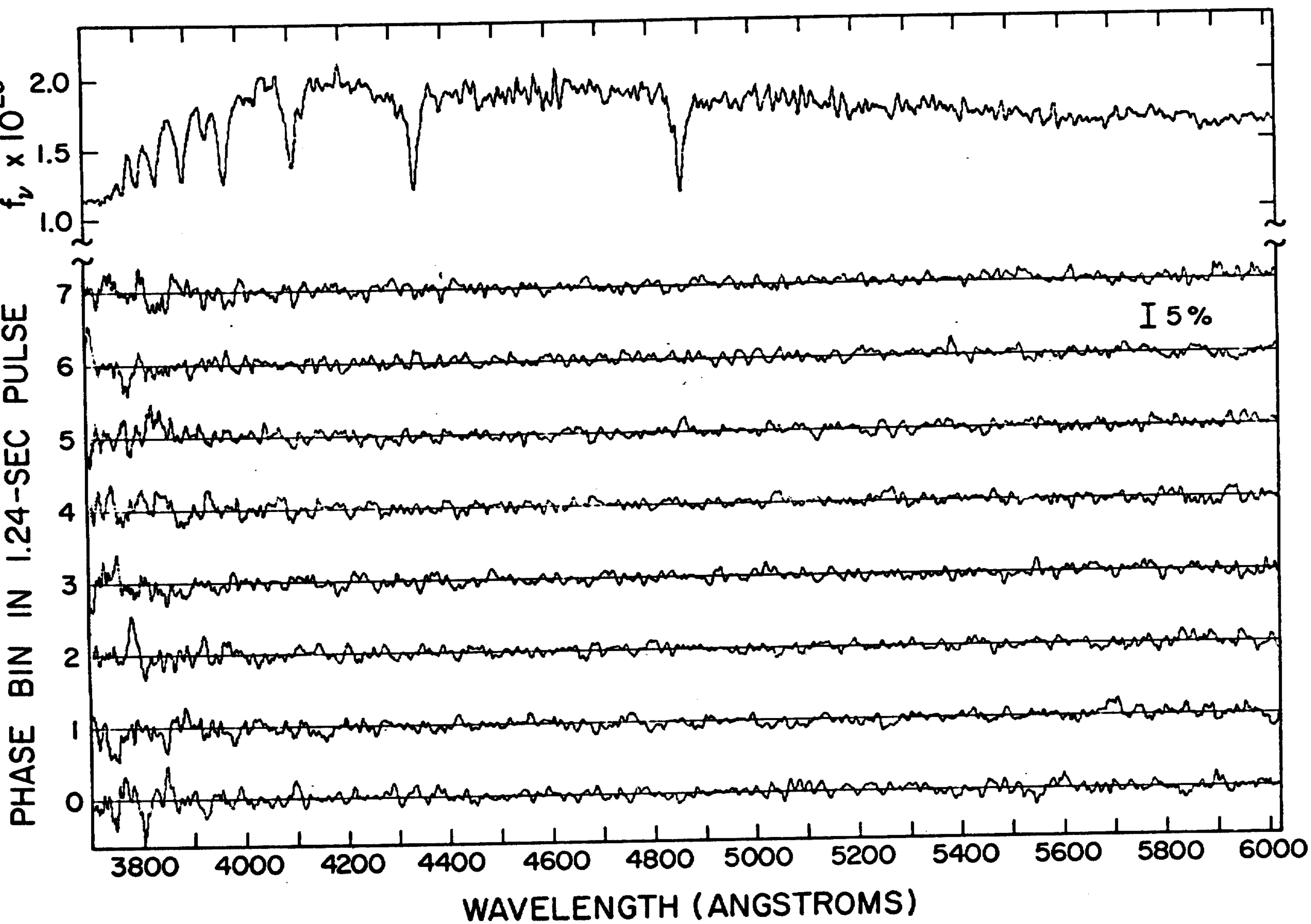

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Figure 1